30 June 1971

Scientific Report No. 6

EXPERIMENTS WITH CHIRP FILTERING OF SURFACE WAVES

LEIF BRULAND
and
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This research has been sponsored in part by the Air Force Office of Scientific Research, through the European Office of Aerospace Research, OAR, United States Air Force, under Contract F61052-68-C-0019.

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DISCLAIMER NOTICE

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Seismological Observatory
University of Bergen
Bergen, Norway

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

Experiments with chirp filtering of surface waves

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Interim

5. AUTHOR(S) (First name, middle initial, last name)

Leif Bruland and Eivind Rygg

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
30 June 1971	38	8

8a. CONTRACT OR GRANT NO.

F61052-68-C-0019

b. PROJECT NO.

AO 292-79

c.

62701D

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

No. 6

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

AF[illegible]

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

TECH, OTHER

12. SPONSORING MILITARY ACTIVITY

Air Force Office of Scientific Research (NPG) 1400 Wilson Boulevard, Arlington, Va. 22209

13. ABSTRACT

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On the basis of the scatter in group velocities found, "arrival time windows" for surface waves from various regions are given.

Dispersion analysis has shown that the assumption of a linear frequency variation in surface waves is not always satisfactory. Therefore, we have allowed for non-linear frequency variation in the chirp filters, and some applications of such filters are demonstrated.

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FOREWORD

The work documented in this report was done at the Seismological Observatory, University of Bergen, Norway, under United States Air Force Contract F61052-68-C-0019.

The authors wish to express their thanks to Associate Professor M. A. Sellevoll for his interest and aid in the initiation and the progress of this work.

ABSTRACT

In connection with the application of linear chirp filters to dispersed surface wave trains recorded at LASA, Montana, a number of events from the SinoSoviet region have been examined in order to determine the predictability of the time of the maximum filter output. The group velocities thus obtained were compared with the group velocities determined by an analyst using ordinary dispersion analysis.

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I. INTRODUCTION

It is well known that the difference in relative excitation of surface waves and body waves is a most powerful discriminant between explosions and earthquakes. (Refs. 1-5). It is also well known that after the introduction of large arrays giving an approximate SNR gain of $\sqrt{N}$ for the short period nondispersive P waves (where N is the number of seismometers), the most serious limiting factor to this discriminant is the detection level of the surface waves.

In this work we have looked into some of the problems connected with the detection of the surface waves. The work follows along two lines, firstly a discussion of the possibility of predicting the arrival times of surface wave trains from specific parts of the world; and secondly the effect of applying differently constructed chirp filters for different regions was investigated.

II. ON THE PREDICTABILITY OF THE GROUP VELOCITY OF THE 20 SEC RAYLEIGH WAVES

In connection with the application of matched filters to dispersed surface wave trains at the Large-Aperture Seismic Array (LASA), Montana, a number of events from the SinoSoviet region have been examined in order to determine the predictability of the time of the maximum filter output. Clearly, if the filter output has several peaks, resulting for example from interfering events, it is desirable to be able to restrict the expected peak from a particular event to a small region on the time axis.

The filters are designed to match dispersed surface wave trains, assuming linear group delay in the frequency range 0.025 - 0.055 Hz (3). The filtering is performed in the frequency domain, and the zero delay frequency used is 0.05 Hz. The filter length referred to later in this text is the length of the time impulse response of the filter in seconds, measured from the 18 sec to the 40 sec wave. The group velocity found by using the maximum filter output, corresponds to the group velocity found by an analyst identifying the arrival time of the 20 sec fundamental mode Rayleigh waves on the raw traces or the beam. The long period beam is formed by using a phase velocity of 3.7 km/sec across the array for all frequencies.

In this context there are certain questions to be answered:

1. Given two or more epicentral regions, what is the difference in the group velocities between the regions and the array, compared to the scatter in group velocities within each region?

2. What is the precision with which the time of the maximum filter output can be estimated for a particular region?

3. Knowing the answers to 1 and 2, is it worth while to map the world as seen from the array in terms of group velocities?

4. Where does the best filter start compared to the first arriving 20 sec waves, as picked by an analyst?

DATA.

A collection of events from Central Asia, the Kurile Islands region and the southwestern border countries of the Soviet Union has been considered. Except for some explosions from eastern Kazakh, only events for which the U.S. Coast & Geodetic Survey (USCGS) epicenters were known, have been used. No poorly recorded or deep event ($h > 60$ km) was included in the collection. The events were divided into three regions according to the type of wavepaths to LASA. Assuming continental structure beneath the Artic Ocean the paths are:

	Region	Wavepath
A	Central Asia	Continental
B	Kurile Islands	Partly oceanic North Pacific Ocean
C	Southwestern border countries of USSR	Partly oceanic North Atlantic Ocean

A Novaya Zemlya and a western Kazakh explosion have been included in region A.

The events are listed in Table I.

PROCEDURE AND RESULTS.

To find the arrival times of the 20 sec waves from the raw traces or the beam, the standard method of Ewing and Press has been used. Arrival times of successive crests are plotted versus crest number, and the resulting points approximated by a smooth curve. A straight line with a slope corresponding to 20 sec period is then adjusted until it is tangent to the smoothed data. The point of tangency gives the arrival time of the 20 sec wave. In many cases, once the period of the surface wave train recorded at LASA has dropped to 20 sec, long portions of the smoothed curve tend to be parallel to the "20 sec slope line". This is of course most pronounced for wave-paths with substantial amounts of oceanic crustal structure, because of the rapid dispersion for waves of about 20 sec period (Fig. 1). The arrival times picked by the analyst represent the <u>beginning</u> of these waves. Thus one can expect the group velocities found by an analyst to be slightly larger than the group velocities calculated, using the time of the matched filter output. USCGS epicenters and origin times have been used in calculating the group velocities.

The average and the extreme values of group velocities and the chirp filter lengths for the different regions are given below. The explosions and earthquakes with continental paths have been separated for comparison.

CONTINENTAL PATHS

Group velocities km/sec

	Matched Filter	Analyst	Filter length (sec)	
High	2.96	3.04	700	Central Asian
Average	2.93	3.00	560	earthquakes
Low	2.90	2.93	350	5 events
High	2.99	3.13	650	Explosions
Average	2.95	3.01	505	9 events
Low	2.90	2.96	350	
High	2.99	3.13	700	Earthquakes and
Average	2.94	3.00	525	explosions
Low	2.90	2.96	350	14 events

PARTLY OCEANIC PATHS

PACIFIC OCEAN

High	3.29	3.34	700	Kurile Islands
Average	3.15	3.17	415	earthquakes
Low	2.97	3.01	250	16 events

NORTH ATLANTIC OCEAN

High	3.11	3.16	800	Southwestern USSR
Average	3.02	3.07	535	border countries earth-
Low	2.89	3.01	400	quakes, 10 events

COMMENTS

Region A.

It is observed that the scatter in group velocities between the explosions is slightly larger than for the earthquakes. However, the latter group consists of only 5 events, and more data may change this. At a typical epicentral distance of 85°, the matched filter peak output would be confined to a time window of 100 sec width, for the group velocities shown above. Thus by using the group velocity 2.94 km/sec, it should be possible to predict the peak output within roughly ± 1 min for this region. The results support the idea of a largely continental crustal structure beneath the Arctic basin.

The (analyst) velocity 3.13 km/sec for one of the Kazakh explosions is anomalously high, the nearest being 3.05 km/sec.

Region B

The group velocities for region B are more widely scattered. This is the case for the hand-picked group velocities, as well as those using the time of the chirp filter output. This might have been anticipated because of the steepness of the oceanic dispersion curve (Fig. 1).

For some of these events the filter outputs show multiple peaks of nearly the same order of magnitude as the main peak. This happens to be the case for the events with the extreme values in region B. Using the secondary peaks for these events, the resulting group velocities would be close to the average (3.15 km/sec). However, the extreme values found by the analyst represent the same events, so no support is given to the idea of restricting the "arrival time window" this way. Consequently, one has to expect this scatter in group velocities, which for a typical distance of 65° corresponds to 4 min on the arrival time axis. ($\pm$ $2\frac{1}{2}$ min using the average velocity given).

Region C.

The oceanic parts of the wavepaths are relatively smaller than for region B, and large parts of the crust under the North Atlantic Ocean are less oceanic than the crust under the North Pacific Ocean.

The scatter in group velocities corresponds to nearly 4 min at the distances involved (85°). The anomalous low velocity 2.89 km/sec corresponds to the event with the maximum filter length. (07.04.68 03:42:00.4, Aegean Sea). On removing this event the width of the arrival-time region drops to about 140 sec ($\pm$ $1\frac{1}{2}$ min), and the average filter length to 505 sec.

DISCUSSION

Obviously, the above results suggest mapping of the world as seen from LASA in terms of group velocities.

All results given above were obtained using vertical recordings. No signal could be detected on the match filtered radial trace for three of the explosions. The signal on the radial trace for one explosion could be detected only if the time window was very restricted. The remaining explosions and all earthquakes could be detected on the chirp filtered radial beam.

The average filter length is longer for region A than for region B. In addition to the difference in epicentral distance this may be due to different dispersion characteristics of the wave paths (Fig. 1). Between 20 and 40 sec the continental Rayleigh dispersion curve covers a broader span on the group velocity axis than the oceanic curve, resulting in longer wave trains in this frequency band.

The difference in average group velocities found by the peak filter output and the analyst, decreases from 0.04 km/sec in region A to 0.02 km/sec in region B. That is, the best filter tends to include larger portions of the continental 20 sec waves. This should be expected because of the different fit to the linear group-delay assumption.

III ON THE APPLICATION OF EXPERIMENTALLY GENERATED CHIRP FILTERS

In the previous section we suggested mapping of the world in terms of group velocities.

We proceed by demonstrating the use of this information in detection methods. In this section we will discuss the use of chirp filters designed to match surface waves. The filters are generated on the basis of the experimentally found frequency variations in the wave trains to be matched.

Capon and Green (2) and Capon and al. (7) used chirp signals with linear frequency-sweep waveforms as matched filters for dispersed wave trains. They found that these waveforms give a satisfactory match to the surface waves and demonstrated considerable enchancement in signal-to-noise ratio. However, dispersion analysis of wave trains from various areas has shown that the linear frequency assumption can not be retained in all cases. Accordingly, in the design of chirp filters we have allowed for non-linear frequency variations.

METHOD

Capon and Green (2) used the reference waveform

$$(1)\quad R(t) = \begin{cases} \sin\left[2\pi\left(f_o t + \frac{f_1 - f_o}{2L} t^2\right)\right], & 0 \leq t \leq L \\ 0, \text{ otherwise}, & \end{cases}$$

where f_0, f_1 are the initial and final frequencies of the wave train whose time duration is assumed to be L seconds.

To allow for non-linear frequency variation, formula (1) should be modified to

$$(2) \quad R(t) = \begin{cases} \sin\left(2\pi \int_0^t F(\tau)\, d\tau\right), & 0 \leqslant t \leqslant L \\ 0, & \text{otherwise,} \end{cases}$$

where, for the special case of a linear frequency variation we have

$$F(\tau) = f_0 + \frac{f_1 - f_0}{L}\tau$$

$F(\tau)$ is the frequency as a function of time in the chirp signal. This frequency variation is found by conventional dispersion analysis of wave trains from the region for which the filter is to be designed.

However, the curves thus found, are encumbered with errors partly due to inaccuracies in reading the peak arrival times and partly resulting from the procedure used to obtain the frequency functions. Corrected frequency curves can be formed by adjusting the chirp signals on the basis of a visual comparison with the wave trains they are supposed to match. This has been done whenever it has been found necessary. Furthermore, because of disturbances in the wave trains to be analyzed, like noise or weak recordings, the chirp signals found often cover only part of the frequency range in the wave trains. In such cases the frequency curves should be extended in some way, and this has been done by some trial extrapolations of the curves, preceding a visual comparison of the resulting filter and the actually recorded wave trains.

Frequency curves for several regions have been obtained this way, and some of these curves are shown in Figs. 2 and 3. As can be seen from Fig. 2 the assumption of a linear frequency variation would give a poor fit to wave trains coming from some regions. Fig. 3 shows the curves used in this paper. The dotted part of the Rayleigh wave curve for West Pakistan is the extension of the original curve. As an example the Rayleigh wave chirp filter for West Pakistan is shown on the figure, and for comparison both the original and the extended version are shown.

DATA AND RESULTS

The data used in designing and testing the chirp filters have been taken from Kongsberg Standard Station. Since these data are on paper, we had to digitize the seismograms and this has of course been a limiting factor on the data base available, and accordingly, on the testing possible to perform.

In Table 2 the events used in this study are listed. Origin times and epicenter positions were taken from the preliminary lists of USCGS, except for some of the explosions where these data were taken from the bulletins of the International Seismological Centre (ISC), Edinburgh.

4 different epicentral regions have been selected, of which West Pakistan is the first to be discussed. From this region the Kongsberg recordings cover a relatively wide magnitude scale; the events of 13. 02. 66 and 08. 12. 66 are both given an $m_b = 5.1$ which is far below the magnitude of events normally detected by the Kongsberg long period system at this distance. The Rayleigh wave chirp filter for this region is

based on the event of 24.01.66, and the wave trains and filter outputs are shown in Figs. 4-7. The amplitude of the surface waves from the 07.02.66 event is compressed by a factor of about 3.

All outputs are given with an output frequency of 0.033 Hz, that is, the peak (or through) on the output trace is located at the arrival of the 30 sec wave.

In the ideal case the output of the filter should look like an autocorrelation function, and we can see that this is nearly the case for all events except for the event of 08.12.66. Despite the fact that this event is given the same body wave magnitude as the event of 13.02.66, the surface waves at Kongsberg are much weaker and are in fact too weak to contain very much energy in the low frequency range covered by the filter. To detect events of low magnitude, the chirp filter should therefore be extended towards higher frequencies. The extended frequency curve and the resulting filter are shown in Fig. 3, and this chirp filter matches the surface waves from all three events fairly well (Figs. 8-10), although the high frequency content in the chirp signal has modified the true autocorrelation form of the output.

The other epicenter regions selected are the Nevada Test Site (NTS), the Rat Islands region and the Nepal-India border region. The frequency curves are shown in Fig. 3, while the raw traces of the events and the filter outputs are given in Figs. 11-18. The Nevada events are all underground nuclear explosions, while for the Rat Islands region there are two earthquakes and one explosion. A Love wave chirp filter has been used for the Nepal-India border region, Rayleigh wave filters for the other regions.

In each of these cases the match between the filters and the surface waves is quite good. However, the events from each region do not vary very much with regard to magnitudes and positions of the epicenters. Therefore, very little information can be drawn from these examples about the consequence of using the same chirp filter for events which differ in magnitude or epicenter position. As to the magnitude variations, however, the results for the West Pakistan region as expected indicate that such variations have little influence on the output, if the chirp filter is designed to cover a broad enough frequency range.

The azimuthal range of each region possible to cover by one filter is of course dependent on the crustal structure between the epicenter and the station, and must be tested in each case. In Fig. 19 the results of applying a Love wave chirp filter to one event from Northern Italy and to one event from Yugoslavia are shown. The filter is designed for Northern Italy. The two events have about the same epicentral distance, and the result shows that the difference in azimuth does not seem to have any great influence on the wave form in this case. However, in cases where multipath propagation can be expected, small differences in azimuth may change the waveforms considerably (8). Among the wave trains considered in this paper, the wave trains from the Rat Islands region seem to consist of groups of waves coming from different azimuths. This is indicated both by the beating of the envelope of the raw traces, and by the form of the filtered traces, which shows several peaks (Figs. 14-16).

In the first part of this report we looked into the predictability of the 20 sec Rayleigh waves from different epicentral regions, as seen from LASA. It might be of some interest to calculate group velocities for different paths to Kongsberg on the basis of the chirp filtered events where maximum peak (or trough) indicates the arrival time of the 30 sec wave. This has been done for all events in Table 2 and the results are listed to the right of the table.

The results show very little scatter in the group velocities within each region, the largest variation is found for West Pakistan, where the group velocity ranges from 3.03 km/sec to 3.10 km/sec. The extremes correspond to the events of lowest and highest magnitude respectively and represent a difference of about 1 min in arrival times.

From one region to another there is, however, a considerable variation. The 30 sec Rayleigh wave group velocity from West Pakistan is about 3.05 km/sec - whereas the corresponding velocity for the Rat Islands events is about 3.60 km/sec. The Love wave paths investigated in this paper are all continental and the group velocities for the 30 sec Love wave are close to 3.5 km/sec.

IV CONCLUSIONS

Chirp filtering may be applied to array data or single sensor outputs. In both cases the presumed arrival time of the surface waves is of great importance, partly because we thus can exclude interfering events, and partly because of saving computing time. Using wave trains recorded at LASA from different epicentral regions it has been found that the arrival time of the 20 sec Rayleigh waves could be predicted within roughly ± 1 min in the best case and ± 2 min in the worst case. These numbers are of course influenced by the size of and distance to the epicentral regions and also by the complexity of the structure between the source and the receiver.

The results indicate that the use of non linear frequency-sweep wave forms as matched filters can be an effective tool in detection of surface waves.

It might be objected that one equally well could use the actually recorded wave trains as matched filters, thus also having the amplitude variations included. However, Capon and al. (7) showed that amplitude variations have very little effect on the signal-to-noise ratio.

Objections relevant to our matched filtering procedure have been put forward recently by Capon (8) in a paper concerning the Rayleigh-wave multipath propagation at LASA. The wave trains he analyzed was shown to consist of several groups of waves arriving from different azimuthal directions. This multipath propagation he explained to be due to the phase-velocity contrast between oceanic and continental regions which led to refractions and reflections at the continental margins. Also, he found that if the multipath propagation for a given epicenter was known, it would still be difficult to predict this effect for an epicenter whose location was significantly different from that of the given epicenter.

These results make the use of master events as matched filters for Rayleigh waves rather doubtful, as emphasized by Capon, and he concluded that the use of chirp wave forms for matched filtering, as recommended by Capon and al. (7), may represent the most reasonable approach to the problem of matched filtering of surface waves.

The objections against the use of master events as matched filters apply to our non-linear chirp filters also, since we are using master events to find the frequency curves. However, if our chirp filters are to be used on recordings from Kongsberg or the Norwegian Seismic Array (NORSAR), the sites of these stations relative to the epicenter regions of main interest remove at least parts of the objections. This is due to the fact that if one is looking for events in Eurasia, the paths to Kongsberg, or NORSAR, are purely continental. Thus no severe geological obstacles causing multipath propagation should be assumed, and this is crudely corroborated by the shapes of the wave trains from these regions (Fig. 5) in contrast to wave trains for example from the Aleutian arc (Fig. 14-16).

Also, in designing the chirp filters, only the first well-defined wave packet is used in the disperison analysis, and thereafter the filters are extended, if necessary, by extrapolation. By this procedure we think that most of the disadvantage by using master events as matched filters is avoided, and at the same time the filters have a frequency variation with a better fit to the actual wave trains than linear frequency-sweep wave forms. Furthermore if we want to assemble matched filters for a large number of regions, actual recordings require considerable more memory space than our frequency curves, which can be reconstructed from a few points (10-20) on each curve.

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Table 1

Date	Origin time	Lat		Long	[illegible]	Region	
27.04.67	23:15:19.7	41.7	N	82.3	91.57	Sinkian	A
20.01.67	01:57:23.1	48.0		102.9	82.33	Mongolia	Earth-
27.05.67	01:42:47.1	39.9		77.3	93.74	Sinkiang	quakes
14.03.66	02:04:36.6	42.5		66.5	91.16	Central Kazakh	
13.03.66	22:30:38.9	42.4		66.5	91.06	" "	
21.10.67	04:59:58.1	73.4		56.4	59.50	Nov. Zemlya	
01.07.68	04:02:01.7	47.9		48.0	83.15	Southw. Russia	
25.03.67	05:58:00	49.8		78.1	83.83	East Kazakh	
29.06.67	02:57:00	"		"	"	" "	
15.07.67	03:27:00	"		"	"	" "	
26.02.67	03:57:57.7	"		"	"	" "	
17.10.67	05:03:58.0	"		"	"	" "	A
24.04.66	10:55:57.1	"		"	"	" "	Explosions
20.10.67	06:03:57.9	"		"	"	" "	
01.11.67	16:30:57.1	48.3		154.4	62.29	Kurile Islands	
07.12.66	17:17:42.0	44.5		151.7	64.54	" "	
05.10.67	15:55:02.8	45.4		150.7	66.11	" "	
25.03.67	22:47:58.4	45.5		151.4	65.66	" "	
21.11.66	12:19:27.3	46.7		152.5	64.31	" "	

Table 1 (cont.)

Date	Origin time	Lat	Long	Δ	Region	
01.04.67	05:57:09.1	46.3	152.0	64.83	Kurile Islands	B
01.04.67	12:23:35.5	45.7	151.8	65.35	" "	
07.10.67	08:28:01.2	49.2	156.3	60.75	" "	
07.06.67	18:16:31.4	47.5	155.4	62.28	" "	
11.01.68	18:08:38.0	46.4	153.3	64.09	" "	
16.12.67	20:53:58.3	51.2	157.7	58.81	E. Coast Kamchatka	
29.01.68	16:42:50.3	43.5	147.2	69.23	Kurile Islands	
30.01.68	01:30:12.6	43.3	148.8	68.55	" "	
24.01.68	14:27:42.8	54.7	167.9	51.73	Komandorsky Isl.	
29.01.68	10:19:05.5	43.6	146.7	69.42	Kurile Islands	
01.04.67	14:00:33.8	45.8	151.7	65.32	" "	
05.02.68	13:34:11.7	40.9	47.6	89.73	E. Caucasus	
22.01.68	20:34:10.0	33.8	46.9	96.3	Iran-Iraq	
13.05.68	02:46:35.7	43.5	40.3	85.43	W. Caucasus	
29.04.68	17:01:57.6	39.2	44.3	90.52	Iran-USSR	C
07.04.67	18:33:31.3	37.4	36.2	89.76	Turkey	
19.08.66	12:22:09.6	39.2	41.7	89.81	"	
07.04.68	03:42:00.4	38.4	24.5	84.51	Aegean Sea	
09.01.68	23:15:42.1	35.5	22.5	86.11	Medit. Sea	
18.04.68	03:08:02.8	41.3	20.3	80.32	Albania	
30.11.67	07:23:51.5	41.5	20.5	80.24	"	

Table 2

Date	Origin time	Δ	Az	m_b	Region	Group velocity (30 sec period) in km/sec	
24.01.66	07:23:07.6	49.662	99.163	5.8	West Pakistan	3.06	Rayleigh
07.02.66	23:06:34.5	49.651	98.733	5.8	"	3.10	"
13.02.66	19:09:47.4	49.744	99.238	5.1	"	3.07	"
08.12.66	02:07:07.4	50.252	99.426	5.1	"	3.03	"
30.06.66	22:15:00.0	73.611	317.697	6.1	Nevada (Expl.)	3.44	"
20.12.66	15:30:00.1	73.645	317.772	6.3	" "	3.44	"
16.09.69	14:30:00.0	73.653	317.823	6.3	" "	3.43	"
15.02.65	01:25:08.8	68.998	6.847	5.8	Rat Islands	3.59	"
18.02.65	23:13:36.3	68.082	5.845	5.4	"	3.59	"
02.10.69	22:06:00.0	68.968	6.991	6.5	" (Expl.)	3.61	"
16.12.66	20:52:13.5	55.622	89.315	5.7	Nepal-India	3.49	Love
27.06.66	10:41:08.6	55.491	89.331	6.0	" "	3.48	"
27.06.66	10:59:18.1	55.541	89.245	6.0	" "	3.50	"
30.12.67	04:19:21.2	15.054	172.932	5.3	Northern Italy	3.53	"
13.04.64	08:30:03.6	15.249	156.724	5.4	Yugoslavia	3.50	"

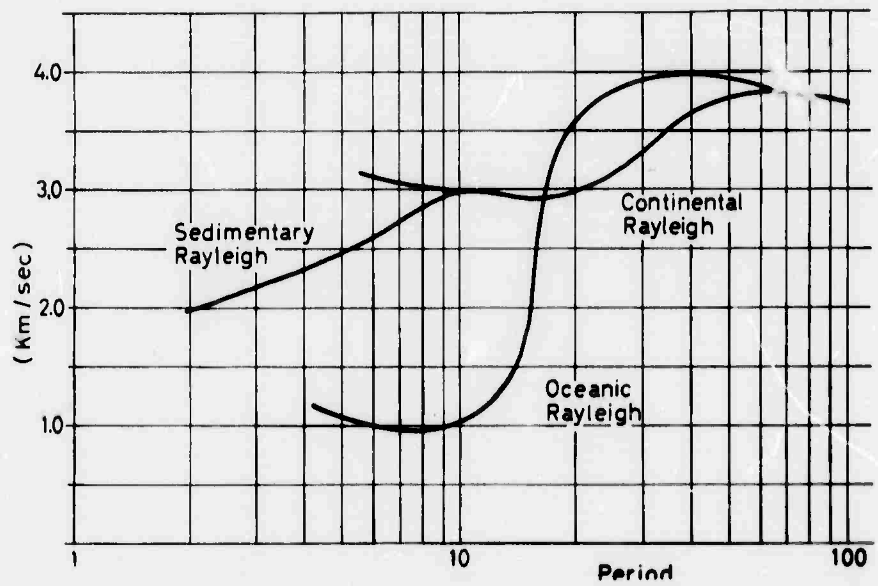

Fig. 1. Summary of observed Rayleigh wave dispersion (After J. Oliver 1962 (6)).

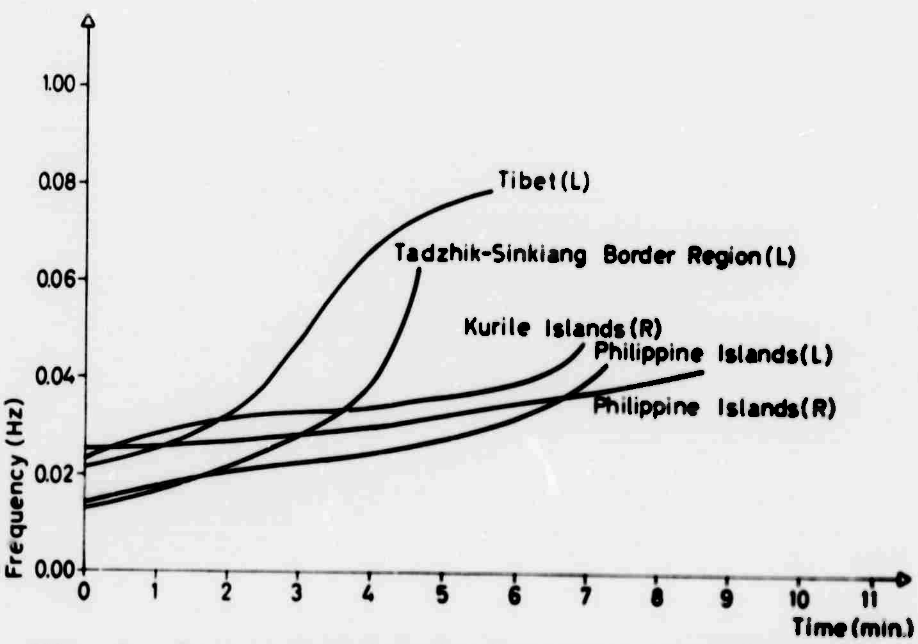

Fig. 2. Curves showing the frequency variation found in Love (L) and Rayleigh (R) wave trains from selected epicentral regions.

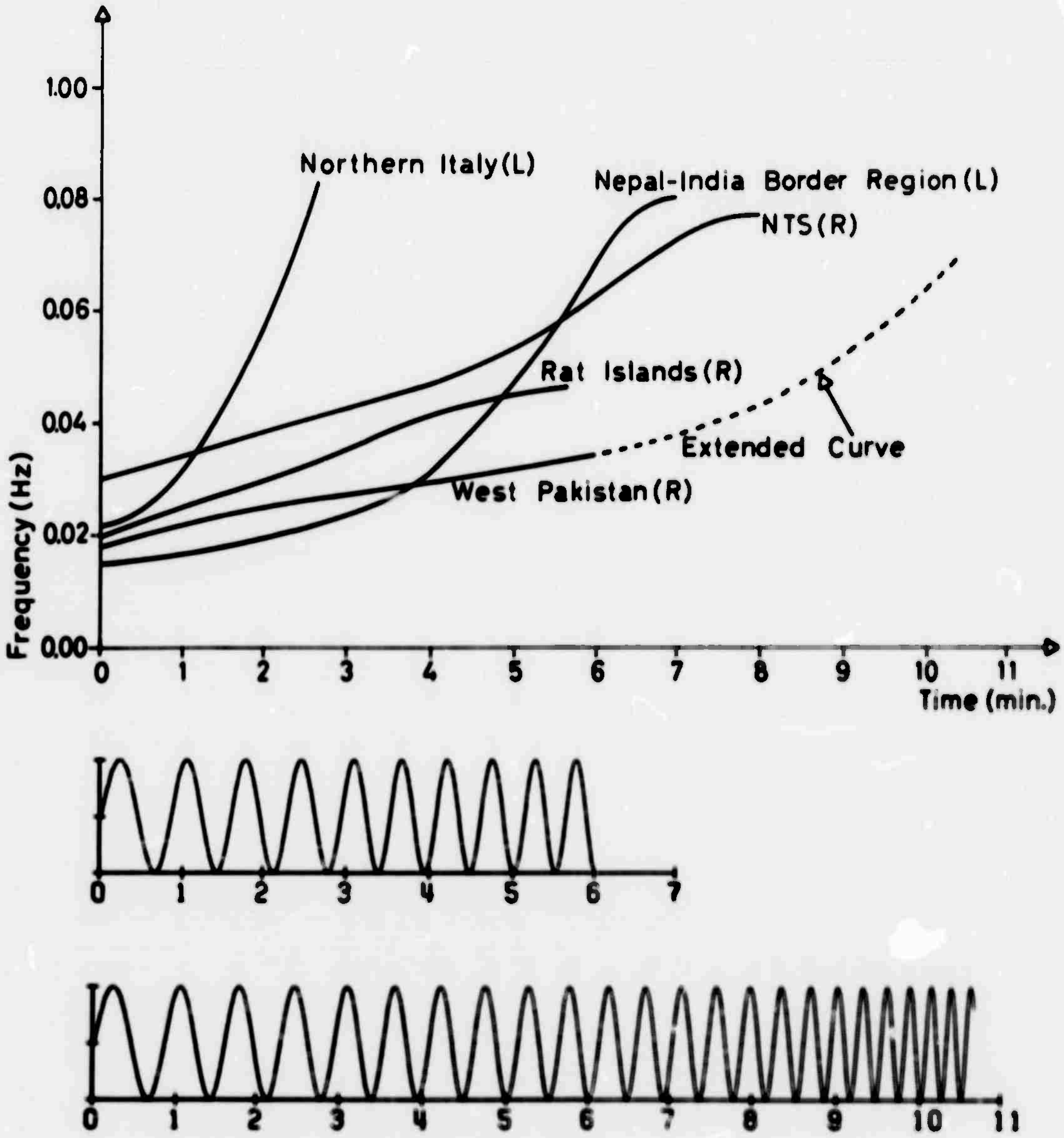

Fig. 3. Frequency curves used in constructing the chirp filters applied in this study. The original and the extended filters for West Pakistan are also shown.

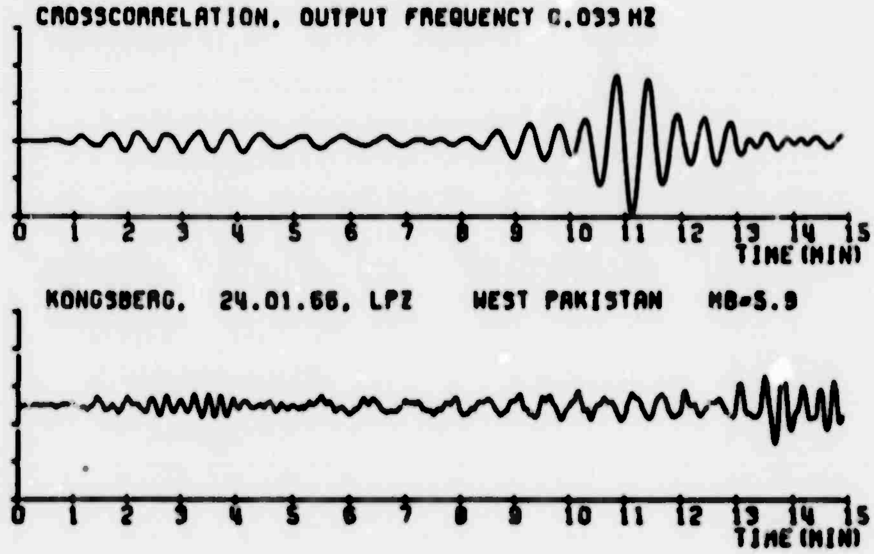

Fig. 4. West Pakistan event. Raw trace (bottom) and chirp filter output (top).

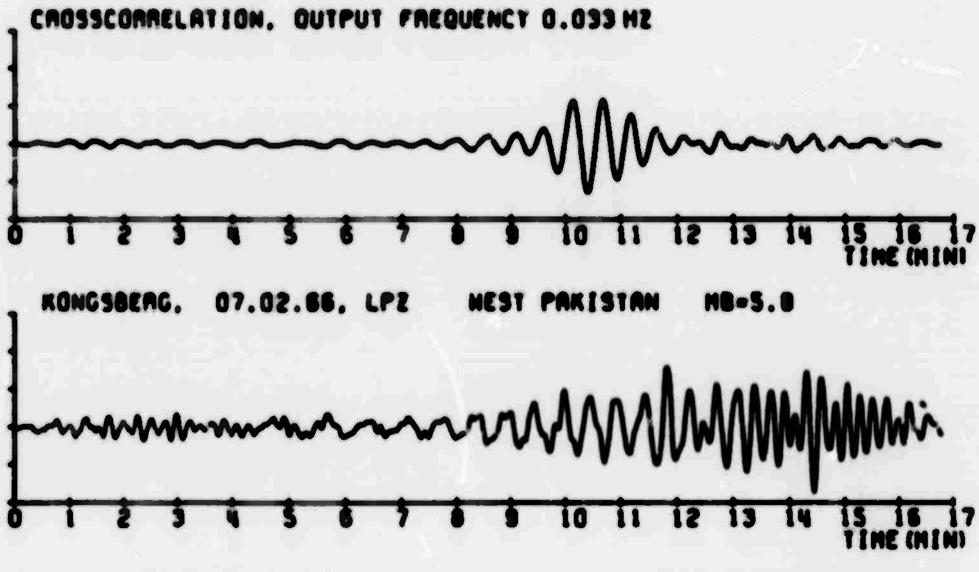

Fig. 5. West Pakistan event. Raw trace (bottom) and chirp filter output (top).

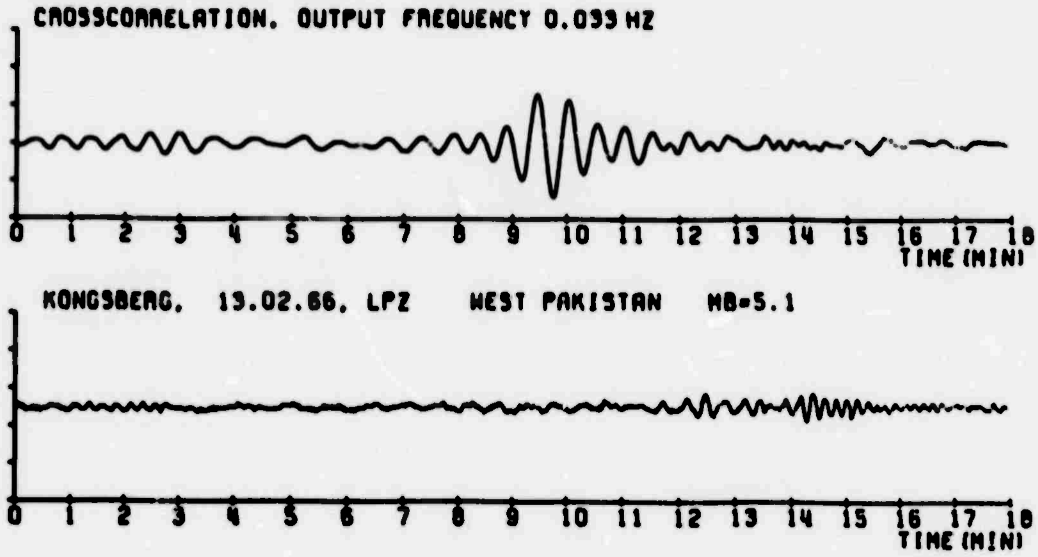

Fig. 6. West Pakistan event. Raw trace (bottom) and chirp filter output (top).

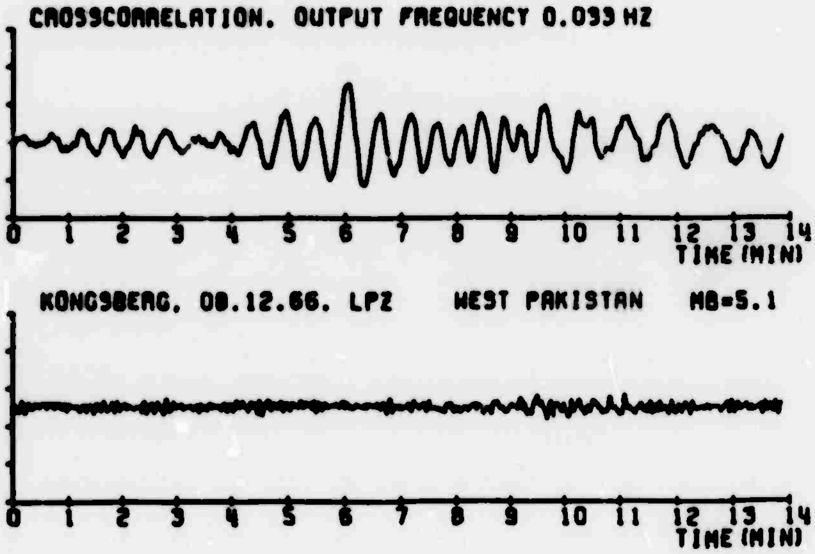

Fig. 7. West Pakistan event. Raw trace (bottom) and chirp filter output (top).

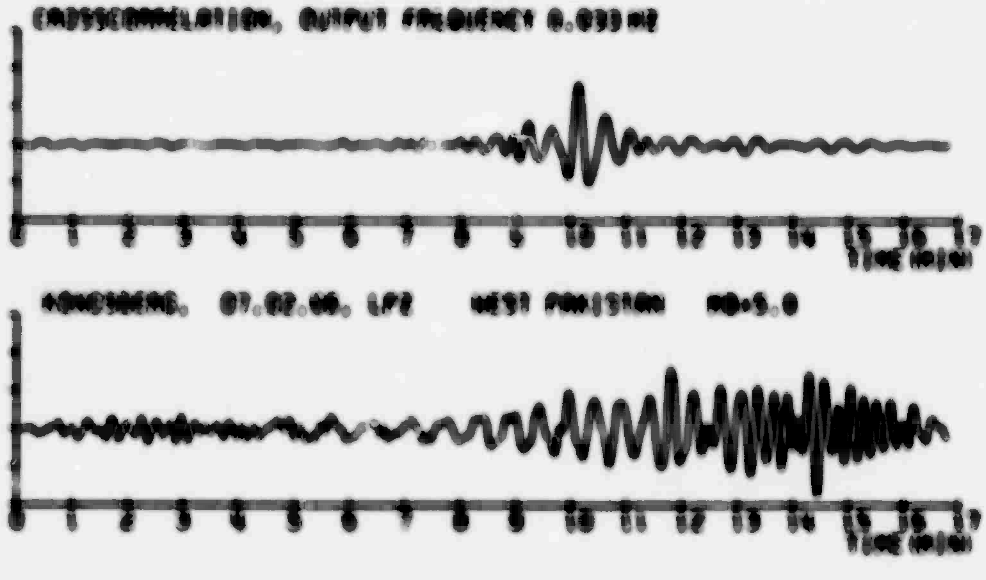

Fig. 8. West Pakistan event. Raw trace (bottom) and extended chirp filter output (top).

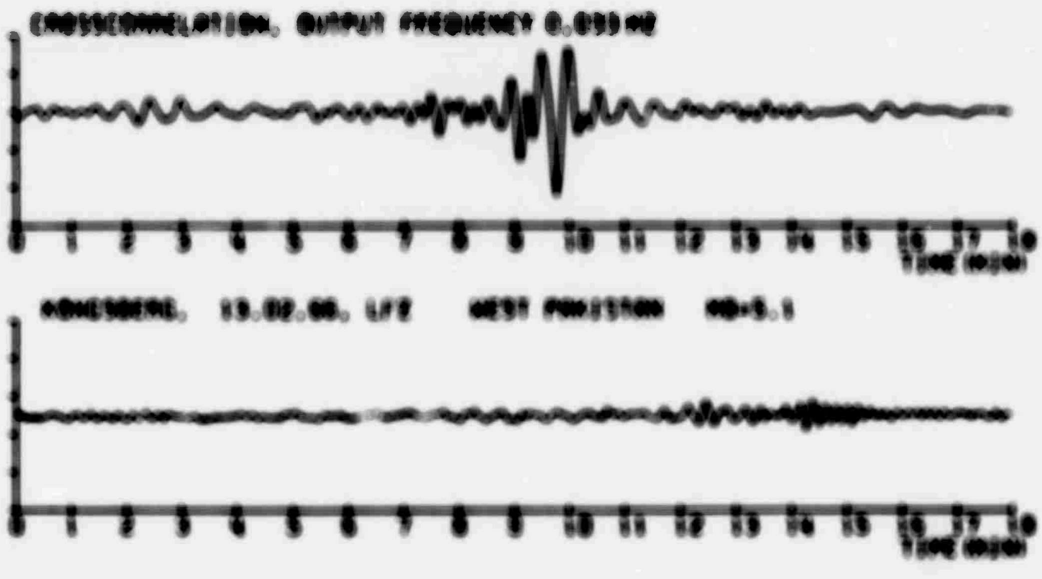

Fig. 9. West Pakistan event. Raw trace (bottom) and extended chirp filter output (top).

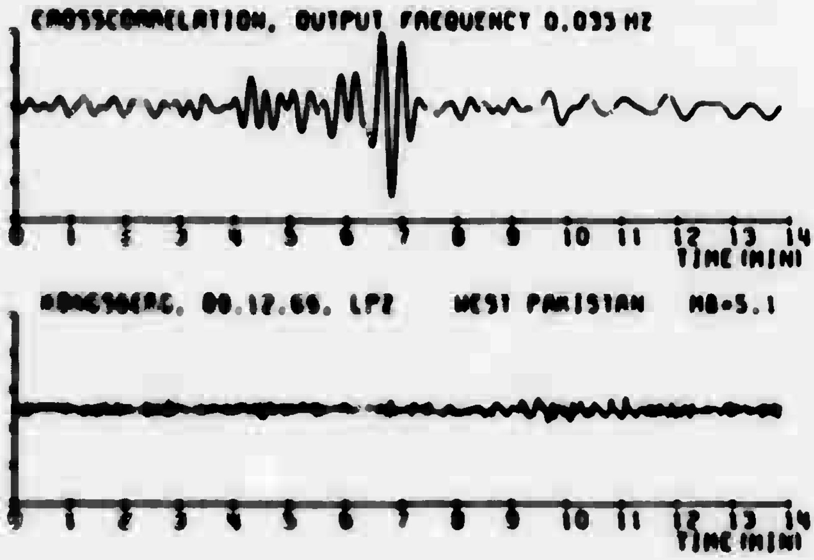

Fig. 10. West Pakistan event. Raw trace (bottom) and extended chirp filter output (top).

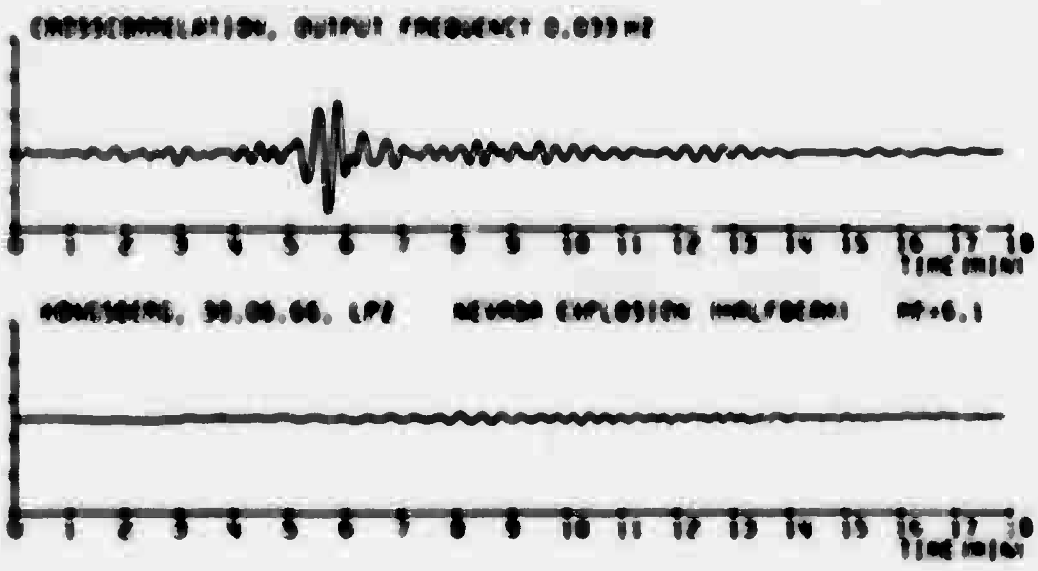

Fig. 11. Nevada explosion. Raw trace (bottom) and chirp filter output (top).

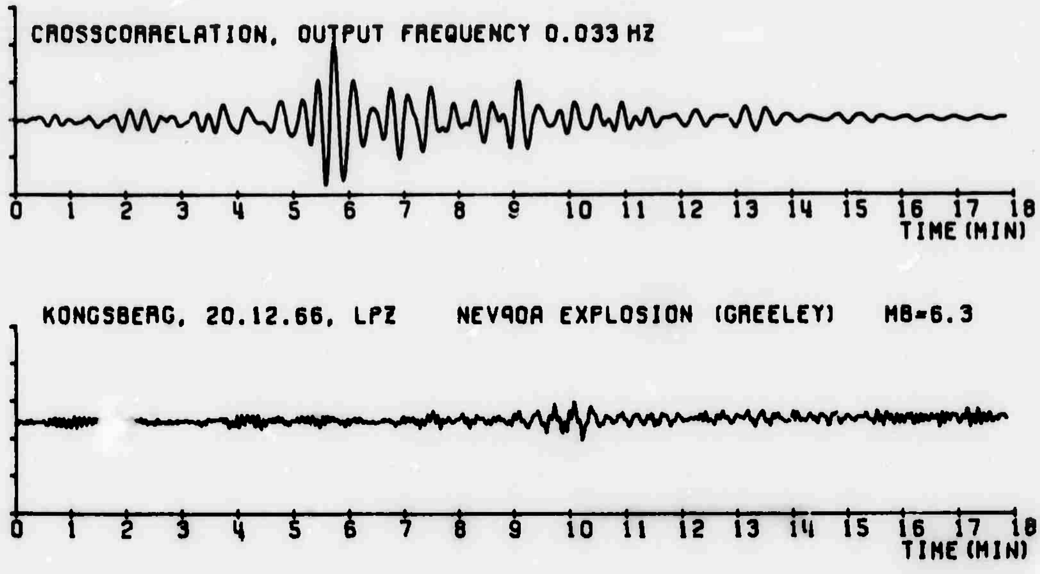

Fig. 12. Nevada explosion. Raw trace (bottom) and chirp filter output (top).

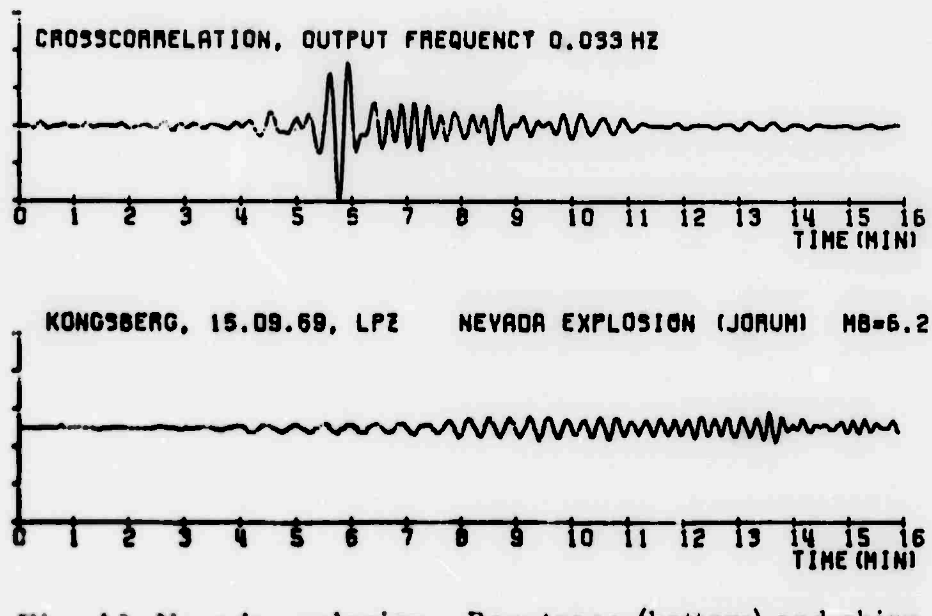

Fig. 13. Nevada explosion. Raw trace (bottom) and chirp filter output (top).

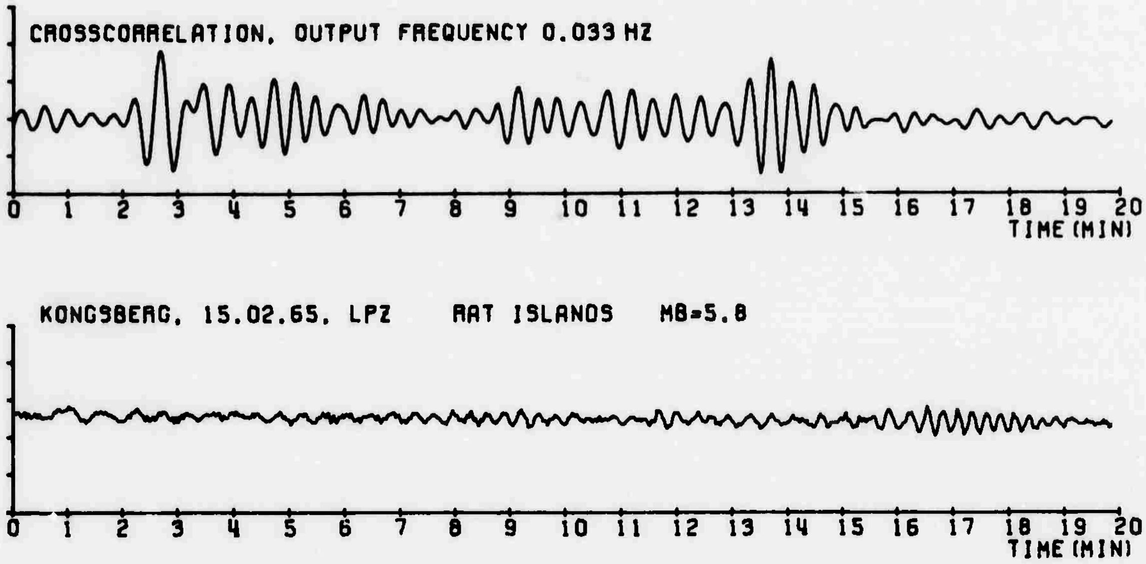

Fig. 14. Rat Islands event. Raw trace (bottom) and chirp filter output (top).

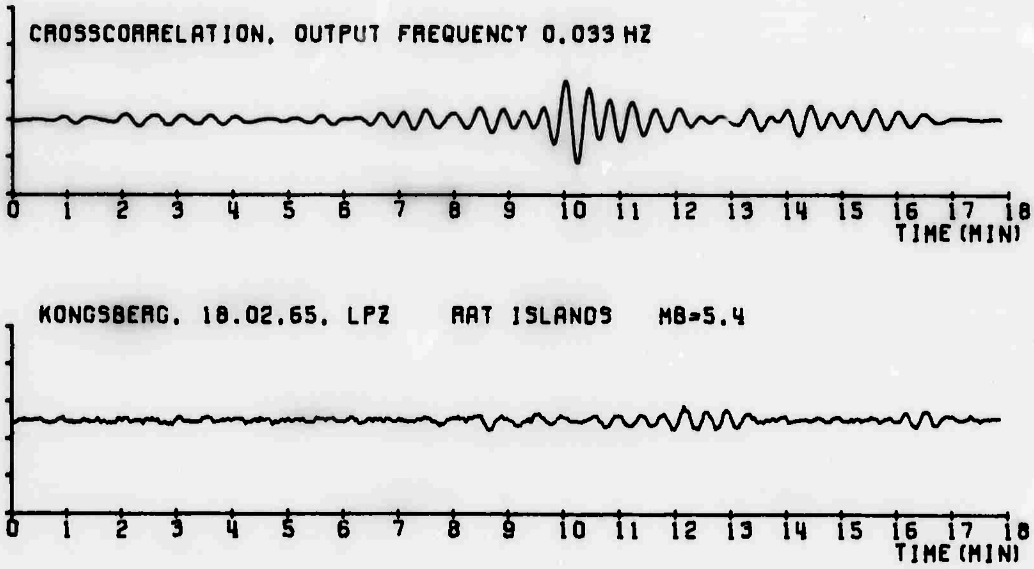

Fig. 15. Rat Islands event. Raw trace (bottom) and chirp filter output (top).

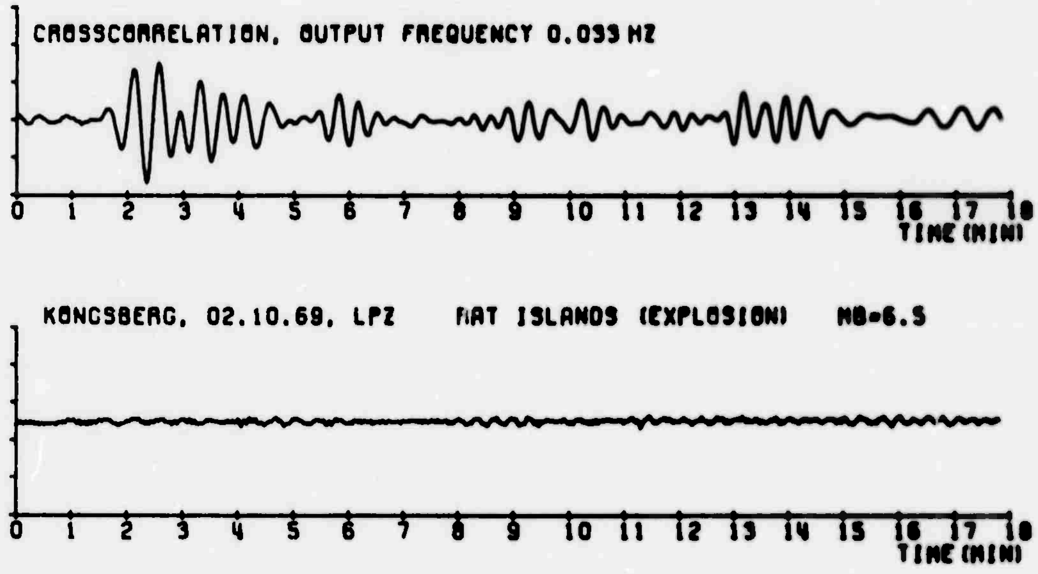

Fig. 16. Rat Islands explosion (Milrow). Raw trace (bottom) and chirp filter output (top).

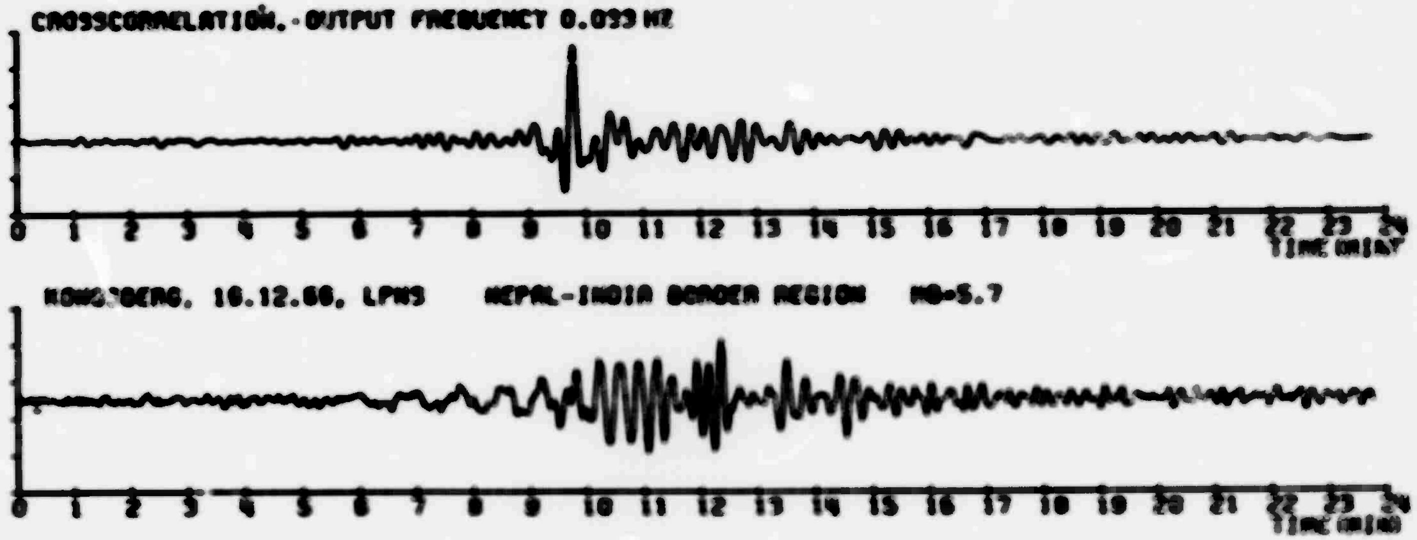

Fig. 17. Nepal-India border region event. Raw trace (bottom) and chirp filter output (top).

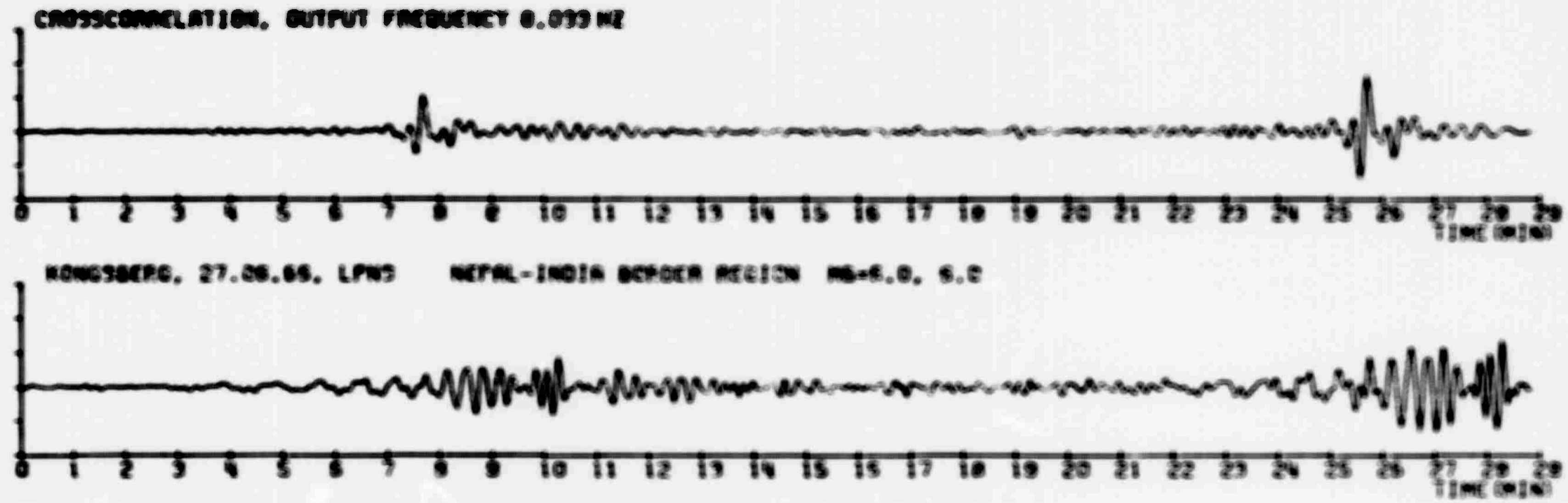

Fig. 18. Nepal-India border region events. Raw trace (bottom) and chirp filter output (top).

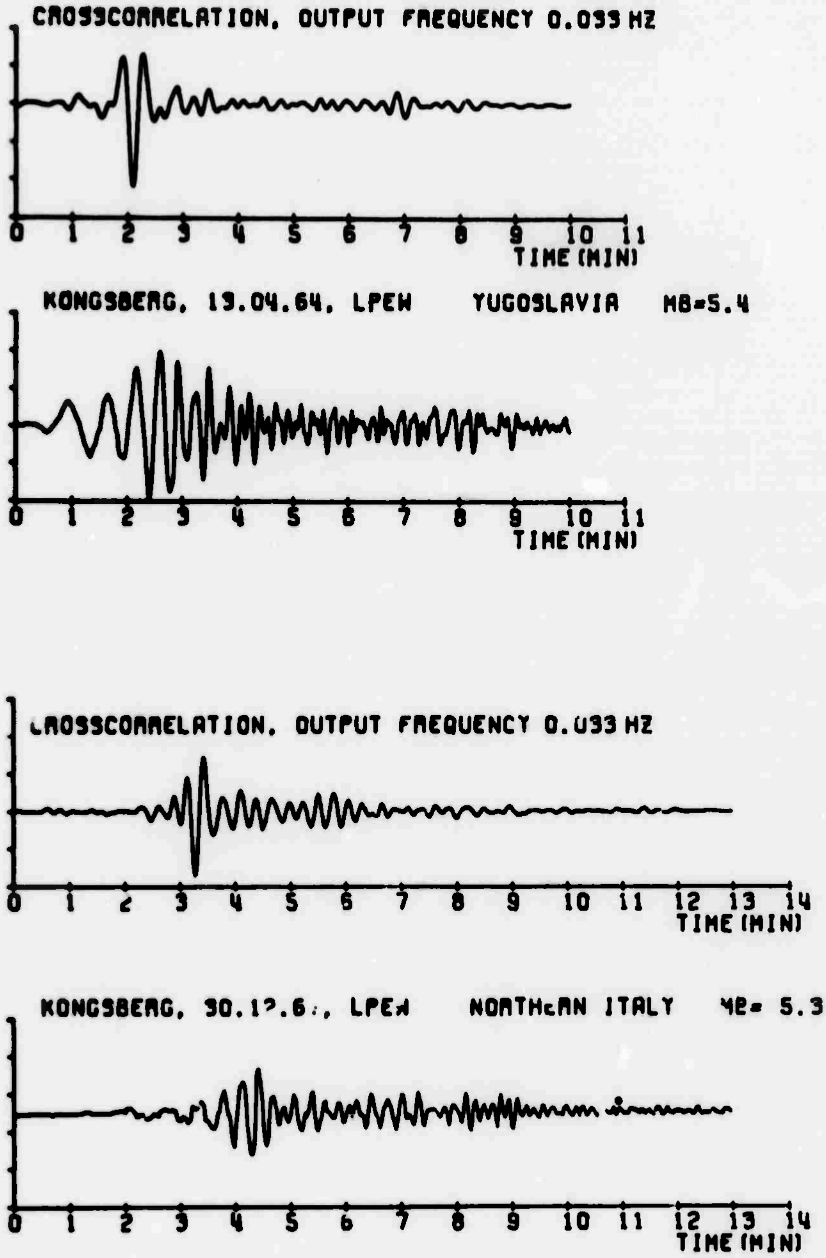

Fig. 19. An example of applying the same filter to two events. The filter has been constructed on the basis of the Northern Italy event. The epicentral distances are approximately the same while the azimuths differ by 15 degrees.